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A review of the ACOUS experiment results

Technical report

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Abstract

This technical report briefly summarizes the results of the Arctic Climate Observations using Underwater Sound (ACOUS) experiment conducted in October 1998 – December 1999. The most important scientific achievements of the experiment are presented. The methods of acoustic inversion for acoustic thermometry in the Arctic Ocean are discussed using the conclusions that were made after processing and interpretation of the ACOUS data. Some technical issues are considered to bring about an improvement of the capability of the prospective acoustic thermometry systems, eliminating in particular certain weakness of the implementation of ACOUS experimental scheme.

I. Introduction

The ACOUS experiment lasted from October 1998 to December 1999. All technical details of the experiment are given in Ref.1. The main results of acoustic thermometry along the ACOUS path are also discussed in Ref.1. An analysis of remote acoustic observations of the ice cover thickness along the ACOUS path is made in Ref.2. The ACOUS experiment is believed to have been successful in general. First of all, the acoustic measurements were capable to detect significant changes in the Atlantic water mass in the Nansen Basin north of the Franz Victory Strait that occurred in August-December of 1999. An analysis of the mode coupling effects applied to inversion of the acoustic data allowed us to obtain a coarse horizontal resolution in the inversion results for water temperature along the propagation path, which was done in ocean acoustic thermometry for the first time. Transmission loss of the ACOUS signals and particularly the modal propagation loss experienced seasonal variations that were basically in agreement with the seasonal change of the ice cover thickness along the acoustic path. This result of the ACOUS experiment proves the capability of long-range acoustic observations to monitor the ice cover in the Arctic Ocean.

On the other hand, processing and the analysis of the ACOUS signals have revealed certain peculiarities of low-frequency acoustic propagation along the cross-Arctic path and the Arctic Ocean environmental conditions that were not expected before the experiment. These peculiarities greatly influence the capability and efficiency of acoustic thermometry and hence they should be thoroughly investigated before planning the next long-term acoustic thermometry experiment in the Arctic Ocean and designing components of a new acoustic thermometry system.

II. Results of the ACOUS experiment

Figure 1 shows the colored intensity plot of the modal arrival pulses of modes 1-3 as a function of the travel time and day of measurements. All of the 107 received signals are synchronized with the arrival time of mode 3 that was measured at the energy center of the modal pulse. The plot demonstrates that the travel time of mode 1 substantially varied during the 14-month observation period. For the last 100 days of measurements, the travel time of mode 2 decreased by almost 1.5 second. The travel time of mode 2 slowly increased by the end of the experiment. The modal pulses also experienced large short-term variations of the pulse shape, amplitude, and travel time, observed for a 4-day interval between the ACOUS transmissions. To explain such complicated variations of the ACOUS signals received on the Lincoln Sea array, a coupled-mode method was used to numerically solve the forward problem of signal propagation at different environmental conditions along the ACOUS path. The main conclusions made from the comparison between the experimental data and the modeling results are as follows:

1. Short-term variations of the modal amplitudes and pulse forms were mainly due to variations of the sound speed in the water column over the Eurasia continental shelf and continental slope within the initial 50-70-km section of the path. These variations greatly influenced the coupled-mode effects over the slope which were strong enough to perturb the amplitudes of modes. Since the perturbation was different at different frequencies in the ACOUS signal frequency band, the modal pulses experienced a considerable distortion that was variable in time due to the sound speed variations.

2. The 1.5-s decrease of mode 1 travel time (and a small increase of mode 2 travel time) was the result of warming of the Atlantic Intermediate Water (AIW) layer in the Nansen Basin at ranges from about 100 to 250 km from the source. The modeling results showed that the warming occurred mainly in the form of spatial expansion of a warm spot of Atlantic water rather than growth of its maximum temperature. The numerical prediction of the modal arrival structure is consistent with the experimental signals, if the warm spot was expanding in both horizontal and vertical directions for the last 100 days of observations. The thermocline that forms the upper boundary of the AIW layer, was moving up, which resulted in a rapid increase of mode 1 group velocity and an expansion of the modal pulse due to stronger coupling of modes 1 and 2.

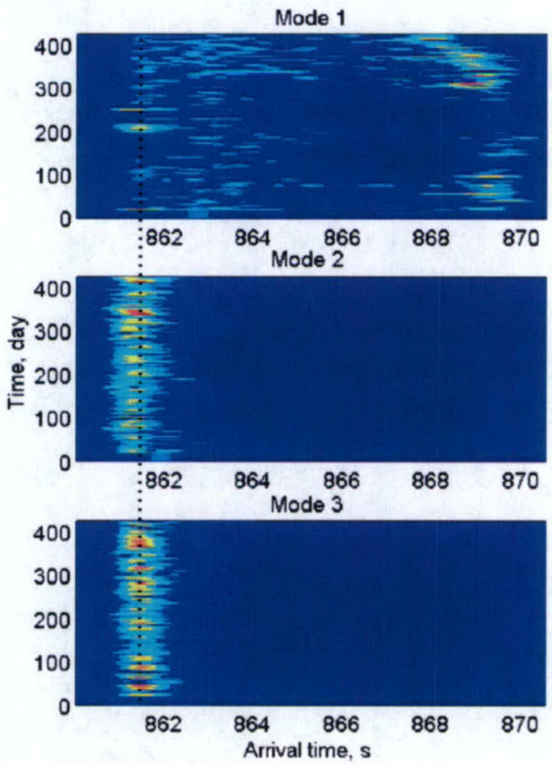

Fig.1. The amplitude of modes 1-3 arrival pulses as a function of the travel time and the day of measurements. Considerable long-term variations of the travel time, amplitude, and pulse width of mode 1 indicated large-scale changes in the Atlantic water temperature and the thermocline depth over the initial 300-km section of the acoustic path. The variations of mode 2 travel time due to those changes are also noticeable, but not so large.

To match the experimental and modeled arrival structures of the modes filtered on the Lincoln Sea array, possible changes in the oceanographic conditions were parameterized in the propagation model using three parameters: the contrast of the warmer Atlantic water spot; the location of the spot on the acoustic path; and the spot width. Empirical orthogonal functions (EOFs) were used to model the background sound speed profile along the path. All of the historical CTD profiles collected within a 200-km wide passage from the source to the receive array were used to build a covariance matrix and calculate the EOFs. It appeared that any of the historical temperature and salinity profiles could be accurately represented by a

combination of only three low-order EOFs (Fig.2). Then we selected the temperature/salinity profiles which were typical along the acoustic path in the 1990s. These profiles were decomposed in the three EOFs. The obtained coefficients of the EOFs were slightly smoothed along the path and resampled up for a uniform and finer spatial resolution. As a result, the background temperature and salinity fields were represented by range-dependent coefficients of the three EOFs (Fig.3).

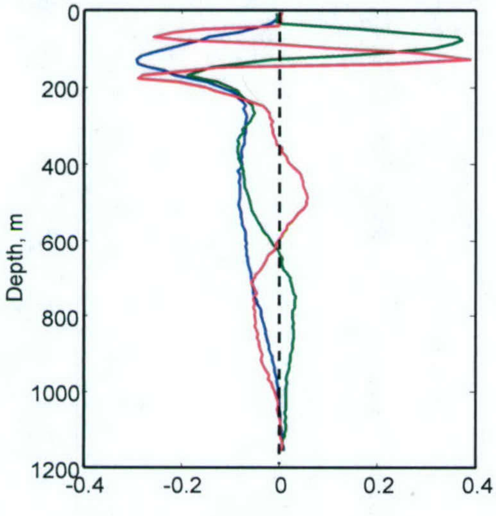

Fig.2. Three low-order EOFs derived from the temperature vertical profiles along the ACOUS path.

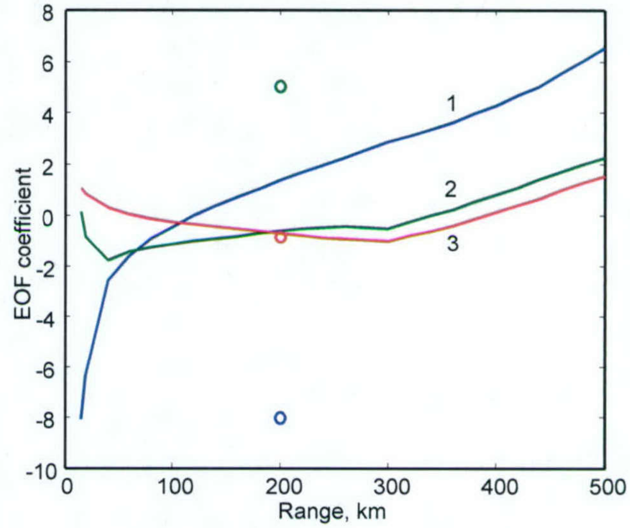

Fig.3. EOFs coefficients that were used to model the background temperature section along the initial 500-km section of the ACOUS path.

Perturbation of the background field was modeled using the warmest CTD profile ever observed in the Nansen Basin north of the ACOUS path. The EOFs' coefficients of this warmest profile were chosen as the maximum perturbation of the background field in the spot, i.e. the maximum contrast of the warm spot. A zero contrast corresponds to the background EOFs' coefficients. The perturbation of the EOFs' coefficients relative to the background ones in front of and behind the spot center was linearly decreased to the background numbers at a certain separation. We varied the location, width, and contrast of the warm spot by moving the location of the "warmest" EOFs coefficients along the path, expanding the perturbation zone, and varying the contrast coefficient.

One of the likeness criteria that we used for matching the acoustic modeling results to the experimental signals, was the correlation of the modal pulse forms in the group of modes 1-4 in the experimental and numerically modeled signals. The combinations of the modal pulses are built on a relative time scale, so that the correlation level depends on the agreement in both the modal pulse shapes and the relative travel times. Such combinations for all of the 107 ACOUS signals were correlated with the modal pulses modeled for different oceanographic scenarios with different numbers of the location, width, and contrast of the AIW warm spot. Figure 4 shows the results of such an "indirect" acoustic inversion for the temperature section along the initial 500-km section of the acoustic path that was restored by matching the modeling results to the experimental signals received in the beginning (upper panel) and the end (lower panel) of observations.

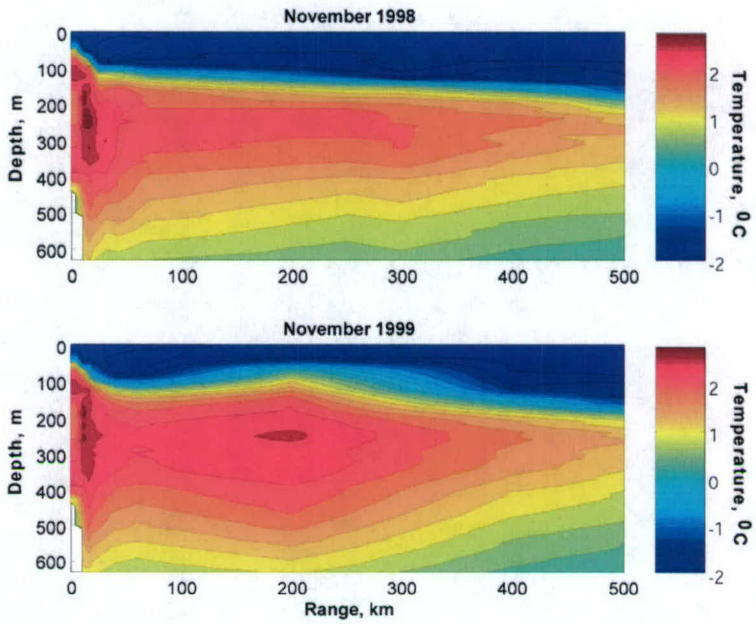

Fig.4. The temperature section shown in the upper panel was modeled using the oceanographic data collected along the initial 500-km section of the ACOUS path in the 1990s. The ACOUS signal parameters observed in the beginning of the experiment are in agreement with this profile.
The bottom panel demonstrates the temperature section that was obtained by inversion of the modal characteristics of the ACOUS signals received in late November - December 1999

The Arctic Ocean climate model developed recently by Michael Karcher [3] predicts the oceanographic processes in 1998-1999 that are similar to those observed through acoustic inversion of the ACOUS experimental data. According to the climate model prediction, the AIW layer north of the ACOUS source location was rapidly warming in July-August 1999 and then the core of warmer Atlantic water was spreading to north up to 200-250 km till December (Fig.5). In the model, the expansion of warmer water is also accompanied by widening of the AIW layer and substantial rising of the thermocline, which is also in agreement with the ACOUS results. The main discrepancy between the acoustic inversion results and the climate model prediction is that the expansion of warm water in the model is gradual from the continental slope to the north, while the acoustic inversion results indicate, most likely, a separate sport of Atlantic water that was warming and spreading from the center at approximately 200 km.

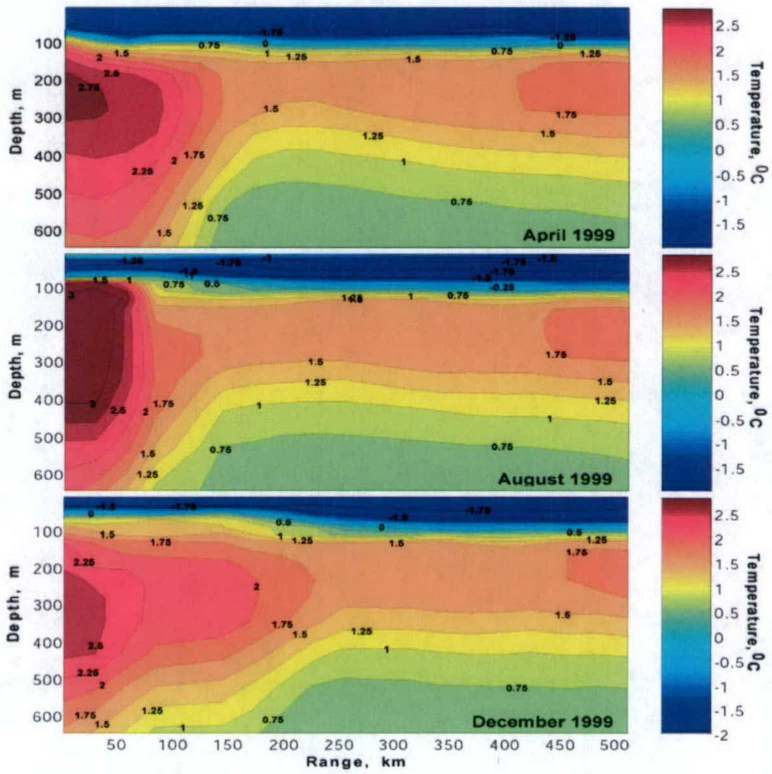

Fig.5. The temperature sections along the initial 500-km section of the ACOUS path in April, August, and December of 1999 derived from the results of numerical simulation using the MOM-2 ocean model by the Geophysical Fluid Dynamics Laboratory [Karcher et. al., JGR, v.108, C2]. Note that the model also shows substantial shoaling of the thermocline at the end of 1999.

3. The seasonal cycle in the variations of the total energy losses of the transmitted signal and the propagation losses of individual modes was observed in the ACOUS experiment (Fig.6, upper panel). The seasonal variation of the total modal energy loss correlates well with the seasonal change of the sea ice thickness determined from numerous upper-looking sonar observations of ice draft from submarines and climate models (Fig.6, lower panel). According to the theory of ice scattering, coherent losses of low frequency signals propagated under ice in the Arctic Ocean depend primarily on the variance and the correlation length of the ice surface roughness. As proven by numerous upward-looking sonar observations of Arctic ice draft, the ice roughness variance closely mirrors the change in the mean ice thickness through a nearly linear relationship. Seasonal melting and growing of sea ice result basically in variations of the mean ice thickness and standard deviation of ice roughness, which influences considerably the acoustic propagation loss and hence can be observed by means of long-range acoustic transmissions, as it was done in the ACOUS experiment. The path-average ice thickness and roughness estimated through inversion of the measured modal propagation loss and numerical modeling are consistent with the recent direct observations of ice draft and the most recent model of seasonal change of the ice thickness [4]. However, the accuracy of such acoustic monitoring of Arctic sea ice needs to be examined in the future experiments by means of ice draft profiling conducted along the acoustic path at the time of acoustic observations. Moreover, numerical modeling has shown that the sound speed profile under

certain conditions may greatly influence the propagation loss of individual modes due to ice scattering. The ice scattering strength of low-order modes, such as mode 1 at 20 Hz, is most sensitive to variations of the sound speed profile. A noticeable amplification of mode 1 amplitude observed on the Lincoln Sea array for the last three months of the ACOUS experiment was most likely the result of the upward displacement of the thermocline that accompanied warming of the AIW layer over the initial section of the acoustic path. Thus, when planning an acoustic monitoring system for remote observations of the Arctic ice cover, it is necessary to take into account the influence of possible variations of the sound speed profile on the acoustic transmission loss.

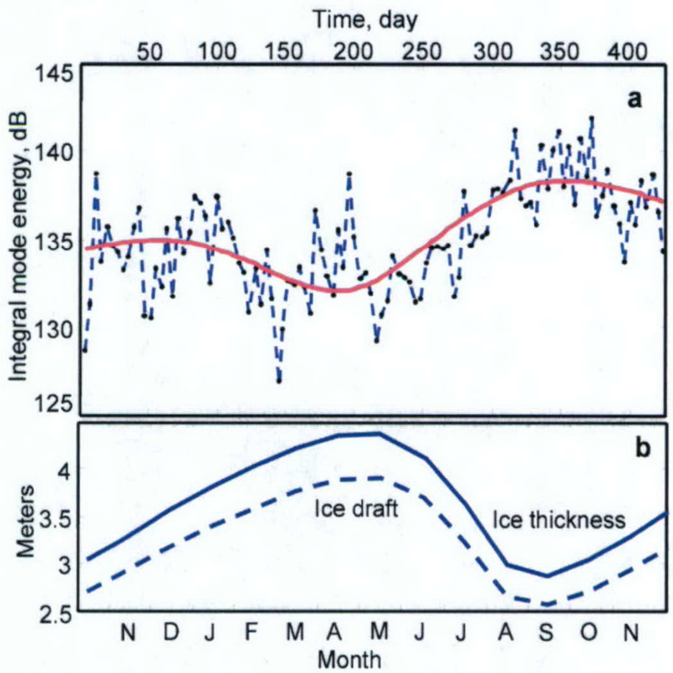

Fig.6. a: Variations of the total energy of modes 1-8 filtered on the Lincoln Sea array. The red line shows the result of wavelet filtration of the long-term component of variations; b: modeled seasonal cycle of ice draft (dashed) and thickness (solid) [D.A. Rothrock et.al., GRL,v.26(23), pp. 3469-3472]. A seasonal component can be clearly seen in the acoustic data. The numerically modeled change of the modal propagation loss due to seasonal variations of the ice thikness corresponds to the observed data.

III. Comments on technical implementation of the ACOUS experiment and recommendations for planning future experiments

1. Acoustic source

The ACOUS source operated well in general, even if such a long-life, low frequency autonomous acoustic source was designed and built for the first time. The major faults of the transmitting complex are as follows:

1) The transmitting complex was designed to autonomously work for at least 2 years, but it stopped working in 14 months. The most likely cause of this is either depletion of the lithium batteries or exceeding the number of recharging cycles of the buffering accumulator. The particular models of both batteries and accumulator should be examined and certified prior to the experiment.

2) The rubidium clock in the source stopped working after 24 days from the start and then the acoustic transmissions were synchronized only to the quartz clock. As a result, the timing was speeding up, which had led to approximately 5-s forestalling of the transmissions. Such an uncertainty is absolutely unacceptable for acoustic thermometry. On the other hand, the results of numerical modeling showed that the travel time of mode 3 at different environmental conditions along the ACOUS path should be stable enough to synchronize the signal arrivals by the arrival pulse of this mode. Even if the environmental change observed for the last months of the ACOUS experiment is so large, the variation of the travel time of mode 3 on the ACOUS path should not exceed 80 ms according to numerical modeling. The fluctuations of the pulse arrival time of mode 3 due to mode-coupling effects are of the same order, which limits the actual time resolution for the inverse problem of acoustic thermometry. Hence the fault of the rubidium clock in the ACOUS source was not too critical. A relatively stable group velocity of higher-order modes, such as modes 3 and 4 at 200 Hz, can be used for timing of the future acoustic thermometry systems especially on shorter, 1-Mm cross-Arctic paths like the ACOUS one. For long-term observations on longer, 3-Mm cross-Arctic paths, accurate timing with a rubidium clock is much more critical.

2. Location of the source.

The location of the ACOUS source was almost optimal from the general point of view. The source was deployed in relatively shallow water, which made it much easier to install the mooring system and provide its stability. Also the source was installed very close to the continental shelf break, which shortened the shallow water section of the propagation path and hence reduced the transmission loss due to the seabed interaction. On the other hand, the ACOUS results and subsequent numerical modeling have shown that such a position of the source has evident disadvantages. The Eurasian continental slope north of the Franz Victoria Strait is steep, which causes strong mode coupling. In presence of a shallower thermocline in this region and large temporal variations of the sound speed profile over the shelf break, the mode coupling leads to large variations of the modal amplitude and pulse form and fluctuations of the modal travel times, which is seen in both ACOUS signals and modeling results. Every mode of the ACOUS signal experienced those variations, which made it much more difficult to interpret the acoustic data. There are two solutions of this problem. The first one is to move the source location to deeper water over the slope (about 1500 m) where the interaction of low-order modes with the seabed is negligible. However, this will complicate much the installation procedure for the acoustic transmitting mooring. The second way is to move the source location to some other

region close to the shelf break, where the thermocline is deeper (and traps mode 1) and the local sound speed variations are smaller. In that sense, the continental shelf north of Severnaya Zemlya is believed to be a more appropriate location than the northern edge of the Franz Victoria Strait.

3. Receive array

The design of the Lincoln Sea array is optimal for filtration of individual modes of the ACOUS signal, which includes the number and positions of hydrophones in the water column [1]. The array was also equipped with an acoustic navigation system to track the array tilt due to variable currents. Unfortunately, the tracking system did not work, which noticeably reduced the mode filtering capability of the array. Prediction of the array tilt and shape can be accurate enough for mode filtration, if the vertical current profile is known. The major constituent of the horizontal current over the Canadian shelf edge in the Lincoln Sea has the tidal period. The tidal cycles of current can be numerically predicted. However, it appeared that the amplitude of tidal variations was dramatically changing during the 14 months of observations (see Fig.7). Moreover, the enormous strengthening of tidal variations observed for certain periods of time has no seasonal or any other regular long-term component. This phenomenon is very interesting (and unexplained) from the oceanographic point of view and hence should be a subject of separate study for Arctic oceanographers. However, for acoustic mode filtering on a vertical array such large and poorly predictable variations of current make it necessary to track the array shape with a navigational system. Using a pressure sensor deployed at the array top, one can determine the periods of weak tidal currents, when the array tilt is small enough for mode filtration without phase compensation for tilt (as was done when processing the ACOUS signals). For periods of stronger current, the array shape can be roughly restored using the data of pressure sensors and hydrodynamic modeling of the array in the field of tidal currents. However, the results of such reconstruction will have an uncertainty in the horizontal orientation of array deviation and hence in the array shape projected onto the vertical plane coinciding with the acoustic path.

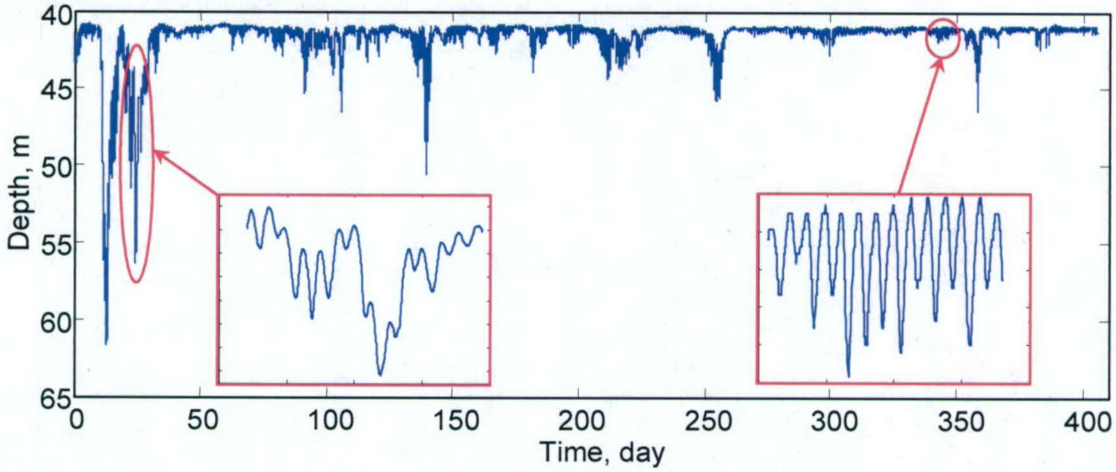

Fig.7. Actual depth of the micro-CTD deployed at the top of the Lincoln Sea array during the ACOUS experiment. Vertical displacements of CTD's pressure sensor has an evident tidal component, which is clearly seen in two pieces zoomed in. Hydrodynamic modeling showed that the maximum vertical displacement of 20 m corresponded to a horizontal deviation of 130 m at the top of the array, which results from the horizontal current of approximately 0.45 m/s at the maximum at 100-150 m and about 0.25 m/s on average (Fig.8). The maximum tilt of 2 degree allowed for accurate mode filtration corresponds to a vertical displacement of approximately 0.5 m. Only a half of the ACOUS signal recordings fell into the time periods that satisfied that condition.

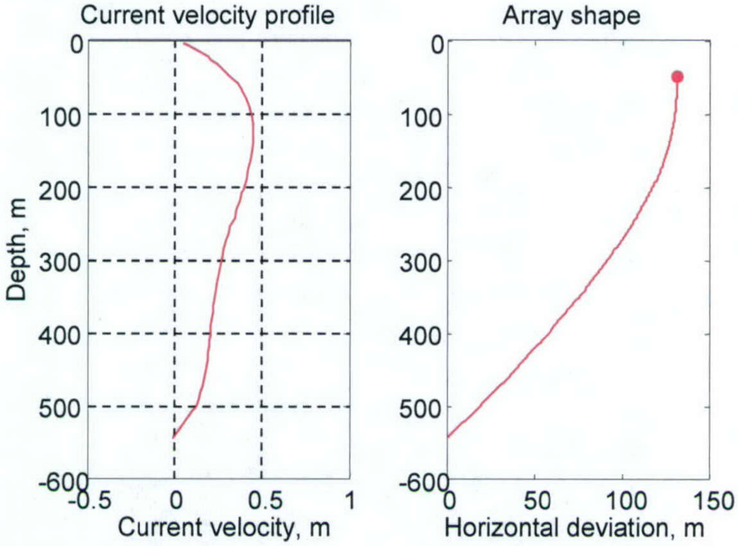

Fig.8. Modeled vertical profile of current that might cause the maximum vertical displacement of 20 m detected by the micro-CTD at the top of the Lincoln Sea array (left panel) and the array shape reconstructed using hydrodynamic numerical modeling (right panel).

The Lincoln Sea array was equipped with 5 micro-CTDs of which the three ones were deployed at the bottom, middle, and top of the array and the other two were placed in the thermocline. Such a distribution of the CTDs was almost ideal for reconstruction of the T/S and sound speed vertical profiles which is accurate enough for numerical calculation of the shapes of acoustic modes (Fig.9). The T/S profiles can be reconstructed using the least mean square approximation for the coefficients of the three EOFs derived from the historical CTD profiles in the Lincoln Sea. However, the two deeper micro-CTDs (at the bottom and middle of the array) were damaged and did not store any data, which substantially reduced the accuracy of reconstruction of the sound speed profile and its variation during the ACOUS observations. Thus it is worthwhile, if the vertical acoustic array in the future acoustic thermometry system is supplied with an array of CTDs, of which the number and locations are determined from the EOF analysis.

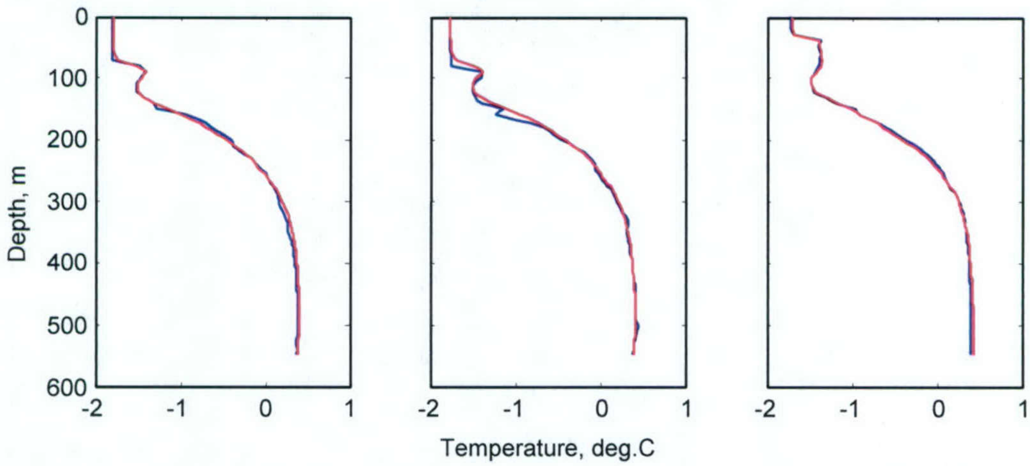

Fig.9. Samples of three different temperature profiles observed in the Lincoln Sea (blue) and their reconstruction using the three most significant EOFs and the temperature numbers that would be measured by the 5 micro-CTDs on the Lincoln Sea array (red).

4. Location of the array

The Lincoln Sea array was deployed close to the Canadian continental slope. The continental slope is steep and hence it may cause considerable coupling of propagated modes. However, in contrast to the environmental conditions over the Eurasian continental slope, the sound speed profile in the Lincoln Sea is less variable and the thermocline is deeper, which considerably reduces coupling of modes 1 and 2, and partly mode 3 at 20 Hz. Of cause, environmental changes on the acoustic path before the Canadian continental slope also lead to variations of the coupling-mode effects over the slope [5], but these variations contribute much less to the variability of the modal arrival pulses on the receive array than the mode-coupling effects over the Eurasian continental slope at the beginning of the acoustic path.

5. Schedule of transmissions and signal parameters

The ACOUS signal duration was approximately 20.5 minutes. For this time period, the signal was stable enough for coherent summation of all of the ten M-sequence periods transmitted by the source. This summation gives an additional gain of almost the maximum number of 10 dB. However, the signal-to-noise ratio of the post-processed ACOUS signals on the Lincoln Sea array was typically about 50 dB. This means that the signal duration could be reduced (to 10 minutes or even less), which would save the energy of the batteries in the emitting complex and allow us to reduce the interval between transmissions. The 4-day time period of the ACOUS transmissions was too long so that the variations of the modal arrival structure on the array due to rapid environmental change were not gradual from one transmission to the subsequent one. This made it much more difficult to interpret the results of acoustic measurements. For the next acoustic thermometry experiment in the Arctic Ocean, it is worthwhile to plan a variable rate of acoustic transmissions that would sample variations of different time scales, like that implemented in the ATOC experiment in the Pacific Ocean.

The central frequency of the ACOUS signals was 20.5 Hz. At this frequency, the group velocity of modes 1 and 2 is highly sensitive to variations of the thermocline depth in the present environmental condition in the Nansen Basin, which has both disadvantages and advantages for acoustic observations. Under such conditions, the group velocity of mode 2 cannot be used for integral acoustic thermometry of the AIW layer along the acoustic path. Also the travel time and ice scattering loss of mode 1 are highly variable. On the other hand, the coupling of modes 1 and 2 over the transition zone from a shallower thermocline to a deeper one allows us to achieve a coarse horizontal resolution for environmental changes along the acoustic path. Numerical modeling showed that the experiment would not be more efficient if the source transmits signals at a different central frequency. The frequency bandwidth of transmitted signals is quite another matter. The bandwidth of the ACOUS signal was about 2 Hz. Within such a narrow frequency band, the effects of environmental changes are nearly similar at different frequencies and hence they cannot be well distinguished through a spectrum analysis of the received signals and individual modes. If the signal frequency band is wider (for example, 21± 2 Hz for the ACOUS path), it would allow us to distinguish the effects of warming in the AIW layer and those due to shoaling of the thermocline.

IV. Conclusions

The ACOUS experiment achieved its principal goal to prove the capability of acoustic thermometry to remotely observe large-scale long-term changes in the ocean environment along the cross-Arctic path. Moreover, the ACOUS observations revealed a new phenomenon related to current warming in the Arctic Ocean, which manifested itself in dramatic change that occurred in the Atlantic water masses in the Nansen Basin north of the Franz Victory Strait in August-December of 1999. According to the ACOUS results, the AIW layer became considerably thicker and warmer and the thermocline rose above a 100-m depth in the Nansen Basin 150-300-km north of the Eurasia continental slope. A thorough theoretical study of the mode-coupling effects on the ACOUS path allowed us to resolve and locate the major change in the water temperature profile along the path. The horizontal resolution of acoustic inversion for the coupled-mode propagation was quite coarse, but it was achieved on a single acoustic thermometry path for the first time. In addition to these important results of acoustic thermometry, the ACOUS experiment showed the feasibility of long-distance acoustic transmissions to monitor the path-average thickness of Arctic sea ice.

The acoustic observations would be even more informative, if the design and parameters of the acoustic thermometry system are optimized to the actual environmental conditions along the path. The spatial and temporal variations of the sound speed profile and the bathymetry along the ACOUS path were very complex. To investigate those variations by means of acoustic transmissions, the future systems will require certain modifications and improvements, which includes in particular: 1) accurate tracking of the array shape and regular measurements of the sound speed profile at the array location for correct filtration of individual modes; 2) precise timing of the emitting and receiving systems synchronized to rubidium clocks (for longer paths); and 3) a higher (or variable) rate of acoustic transmissions that would adequately sample environmental changes of a broader time scale from the tidal variation to the interannual and climatic ones. A proper selection of the cross-Arctic acoustic path is also important for achieving more informative results of acoustic thermometry and better knowledge of the current processes in the waters of the Arctic Ocean.

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